HD 140283: A Star in the Solar Neighborhood that Formed Shortly After the Big Bang[1]

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ABSTRACT

HD 140283 is an extremely metal-deficient and high-velocity subgiant in the solar neighborhood, having a location in the HR diagram where absolute magnitude is most sensitive to stellar age. Because it is bright, nearby, unreddened, and has a well-determined chemical composition, this star avoids most of the issues involved in age determinations for globular clusters. Using the Fine Guidance Sensors on the *Hubble Space Telescope*, we have measured a trigonometric parallax of 17.15 ± 0.14 mas for HD 140283, with an error one-fifth of that determined by the *Hipparcos* mission. Employing modern theoretical isochrones, which include effects of helium diffusion, revised nuclear reaction rates, and enhanced oxygen abundance, we use the precise distance to infer an age of 14.46 ± 0.31 Gyr. The quoted error includes only the uncertainty in the parallax, and is for adopted surface oxygen and iron abundances of $[\mathrm{O/H}] = -1.67$ and $[\mathrm{Fe/H}] = -2.40$. Uncertainties in the stellar parameters and chemical composition, especially the oxygen content, now contribute more to the error budget for the age of HD 140283 than does its distance, increasing the total uncertainty to about ± 0.8 Gyr. Within the errors, the age of HD 140283 does not conflict with the age of the Universe, 13.77 ± 0.06 Gyr, based on the microwave background and Hubble constant, but it must have formed soon after the big bang.

Subject headings: astrometry — stars: distances — stars: evolution — stars: individual (HD 140283) — stars: Population II

1.   Introduction: The Oldest Stars

The age of the Universe is 13.77 ± 0.06 Gyr, based on data on the cosmic microwave background (CMB), baryon acoustic oscillations, and Hubble constant (Bennett et al. 2012). Precise ages for the oldest and most metal-deficient stars can date the onset of star formation (e.g., Bromm & Larson 2004) following the big bang. Moreover, because the oldest stars must be younger than the Universe, precise ages provide a strong test of the consistency of stellar and cosmological physics.

As recently as the 1990's, there appeared to be a conflict between relatively high ages found for stars in Galactic globular clusters (GCs), and a relatively low age of the Universe from determinations of the Hubble constant. This situation changed with the discovery of evidence for an accelerating expansion of the Universe (Riess et al. 1998; Perlmutter et al. 1999), improved precision in determinations of the Hubble constant (Freedman et al. 2001), and measurements of the CMB. At about the same time, the first studies to use parallaxes of local subdwarf calibrators from the *Hipparcos* mission (Perryman et al. 1997) to derive GC distances suggested that these systems are younger than previously thought (Reid 1997; Gratton et al. 1997; Chaboyer et al. 1998; but see Pont et al. 1998). However, the increased cluster distance moduli reported in these papers, which were responsible for the reduced ages, tended to be $\sim$0.2 mag larger than currently favored estimates (as given in the latest version of the online catalog maintained by Harris 1996).

By the early 2000s, refinements in stellar-evolution modeling (most notably the inclusion of diffusive processes) again reduced GC ages to values that appeared to be less than the age of the Universe (VandenBerg et al. 2002), only to be followed by a revision of the rate of the ^{14}N$(p, \gamma)^{15}$O reaction, which implied increased ages at a given turnoff luminosity by 0.7–1.0 Gyr (Imbriani et al. 2004). Although it is unlikely that there will be further significant revisions to basic stellar physics, because most of the ingredients of stellar

models have been carefully examined during the past decade, it is still unclear whether or not GC ages are compatible with the age of the Universe. In addition to the issue of distances, age determinations of stars in GCs require knowledge of interstellar extinction and chemical compositions, including the abundances of individual heavy elements.

An alternative approach to stellar chronology is to determine ages of extreme Population II subgiants in the solar neighborhood based on direct trigonometric parallaxes, combined with state-of-the-art theoretical isochrones appropriate to the detailed composition of each star. This method bypasses most of the problems associated with the much more distant clusters.

2.   The Extreme Halo Subgiant HD 140283

The ideal solar-neighborhood target for an age determination based on a precise parallax would be a nearby extremely metal-deficient star, with a well-determined chemical composition based on high-resolution spectroscopy, which has begun to evolve off the main sequence in the Hertzsprung-Russell diagram (HRD). The one star that best satisfies these criteria is HD 140283, a bright (7th-mag) Population II subgiant with a very low metal content ([Fe/H] $= -2.40 \pm 0.10$; Casagrande et al. 2010). HD 140283 played an important role in astronomical history as the first high-velocity star recognized—a century ago—to have an anomalously early spectral type for its low luminosity (Adams 1912), making it a so-called "A-type subdwarf." Moreover, HD 140283 (along with another similar subdwarf, HD 19445) was subsequently the first star shown, through spectroscopic analysis, to have a much lower heavy-element content than the Sun (Chamberlain & Aller 1951; see also the historical discussion by Sandage 2000). This explains the superficial resemblance of its extremely weak-lined spectrum to that of a hotter star of normal composition, in spite of a surface temperature corresponding to an early G-type star. Thus HD 140283 was the key to

the realization that the chemical elements heavier than helium are synthesized during stellar evolution (Burbidge et al. 1957), making low abundances of the heavy elements a hallmark of the oldest stars. With improved photometry, trigonometric parallaxes, and spectroscopic analyses, it was recognized later (Cohen & Strom 1968; Cayrel 1968) that HD 140283 is actually a slightly evolved subgiant, rather than a classical subdwarf, placing it at the ideal location in the HRD where the absolute magnitude is most sensitive to stellar age.

The *Hipparcos* parallax of HD 140283 is 17.16 ± 0.68 mas, according to a recent re-analysis of the *Hipparcos* data (van Leeuwen 2007). The corresponding luminosity, combined with isochrones calculated without element diffusion, implied an age for the star greater than ~ 14 Gyr; and if HD 140283 were used to calibrate the distances of GCs, the oldest clusters were found to have ages of at least 15 Gyr (VandenBerg 2000). Inclusion of effects of helium diffusion in the calculations reduced the implied age of HD 140283 to 13.5 ± 1.5 Gyr (VandenBerg et al. 2002), but still with an uncomfortably large uncertainty. The largest contributor to this relatively large error in the age is the uncertainty in the *Hipparcos* parallax. As noted in §1, the revision of the $^{14}N(p, \gamma)^{15}O$ reaction that occurred two years later would have increased the predicted age to ~ 14.3 Gyr, if all of the other factors that play a role in the age determination were left unchanged.

3. Hubble Space Telescope FGS Astrometry of HD 140283

At the present time, the most precise trigonometric parallaxes that can be obtained at optical wavelengths are from the Fine Guidance Sensors (FGS) on the *Hubble Space Telescope* (*HST*). The FGS have been shown to be capable of yielding parallaxes with better than 0.2 mas precision (e.g., Benedict et al. 2007). Because of the importance of the ages of the oldest stars, we undertook observations of HD 140283 aimed at improving the precision of its parallax, and reducing any systematic errors, relative to the *Hipparcos*

result.

We made FGS observations of HD 140283 at 11 epochs between 2003 August and 2011 March, at dates close to the biannual times of maximum parallax factor. The FGS are interferometers that, in addition to providing guiding control during imaging or spectroscopic observations, can measure precise positions of a target star and several surrounding astrometric reference stars with one FGS while the other two guide the telescope. These positional measurements are corrected for differential velocity aberration, geometric distortion, thermally induced spacecraft drift, and jitter. Because of refractive elements in the FGS optical train, an additional correction based on the $B - V$ color of each star is applied. Moreover, due to its brightness, HD 140283 itself was observed with the F5ND neutral-density attenuator, while the reference stars were observed only with the F583W filter element. Thus it was necessary to apply a "cross-filter" correction to the positions of HD 140283 relative to the reference stars.

The data from all epochs were combined using a four-parameter (translation in x and y, rotation, and scale) overlapping-plate technique to form a master plate. We employed the least-squares program GAUSSFIT (Jefferys, Fitzpatrick, & McArthur 1988) to solve for the parallax and proper motion of the target and the six reference stars, as outlined in detail by Benedict et al. (2011). Since the FGS measurements provide only the relative positions of the stars, the model requires input estimated values of the reference-star parallaxes and proper motions, in order to determine an absolute parallax of the target. These estimates (see next paragraph) were input to the model as observations with errors, which permits the model to adjust their parallaxes and proper motions (to within their specified errors) to find a global solution that minimizes the resulting χ^2 fit.

As just noted, the solutions for parallax and proper motion of the target star require estimates of the distances and proper motions of the background reference stars. We made

the distance estimates using ground-based spectroscopy and photometry of the six reference stars (whose V magnitudes range from 11.9 to 16.6). Due to space limitations, the details of this process will be published elsewhere, but we summarize here. For spectral classification, we obtained digital spectra with the WIYN 3.5m telescope and Hydra spectrograph at Kitt Peak National Observatory, and with the 1.5m SMARTS telescope and Ritchey-Chretien spectrograph at Cerro Tololo Interamerican Observatory (CTIO). The classifications were then accomplished through comparison with a network of standards obtained with the same telescopes, assisted by equivalent-width measurements of lines sensitive to temperature and luminosity.

Photometry of the reference stars in the Johnson-Kron-Cousins BVI system was obtained with the SMARTS 1.3m telescope at CTIO, using the ANDICAM CCD camera, and calibrated to the standard-star network of Landolt (1992). Each star was observed on five different photometric nights in 2003, 2005, and 2007. To estimate the reddening of the reference stars (assumed to be the same for all six, since their distances place them well beyond the dust of the Galactic disk and also well behind the unreddened HD 140283 itself), we compared the observed $B - V$ color of each star with the intrinsic $(B - V)_0$ color corresponding to its spectral type (Schmidt-Kaler 1982), and calculated the average $E(B - V)$. We also used the extinction map of Schlafly & Finkbeiner (2011), as implemented at the NASA/IPAC website[1], to determine the reddening in the direction beyond HD 140283. Both methods yielded $E(B - V) = 0.14$, which was used to correct all of the magnitudes and colors. Finally, we estimated the distances as follows: (1) For stars classified as subgiants and giants, we fitted them by interpolation to a fiducial sequence $[M_V$ vs. $(V - I)_0]$ for the old open cluster M67 (Sandquist 2004). (2) For the stars classified as dwarfs, we derived calibrations of the visual absolute magnitude, M_V, against $B - V$

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[1]`http://ned.ipac.caltech.edu`

and $V - I$ colors through polynomial fits to a sample of 791 single main-sequence stars with accurate BVI photometry and *Hipparcos* or USNO parallaxes of 40 mas or higher ($d < 25$ pc), which is provided online by I. N. Reid[2]. A correction for metallicity, estimated from each star's position in $B - V$ vs. $V - I$, was applied. We tested our algorithm by applying it to 136 nearby stars with accurate parallaxes and a wide range of metallicities listed by Casagrande et al. (2010). We reproduced their known absolute magnitudes with an rms scatter of only 0.28 mag. At the distances of the reference stars, ranging from 650 to 1700 pc, this scatter corresponds to parallax errors of 0.08 to 0.20 mas.

The initial proper-motion estimates for the reference stars were taken from two independent catalogs: UCAC4 (Zacharias et al. 2012) and PPMXL (Roeser, Demleitner, & Schilbach 2010). We noted that the proper motions disagreed between the UCAC4 and PPMXL catalogs for several of our reference stars by more than the stated errors. Thus we ran two independent solutions based upon the two catalogs. To minimize contamination of the FGS results by large input catalog errors, we applied an iterative technique whereby the FGS proper motions that were output from the solution using either UCAC4 and PPMXL as input were used as the input proper motions in a second iteration. This resulted in good agreement ($\sim 1\,\mathrm{mas\,yr^{-1}}$) between the relative proper motions of the reference stars, but a systematic difference in the absolute values. The solution based upon the UCAC4 catalog reproduced the *Hipparcos* proper motion of HD 140283 quite well, with the solution based on PPMXL differing by $\sim 3\,\mathrm{mas\,yr^{-1}}$. Both models yielded parallaxes of HD 140283 that agreed within 0.03 mas.

For our final solution, we used the UCAC4 catalog and the iterative procedure described above. The resulting absolute parallax of HD 140283 is 17.15 ± 0.14 mas ($d = 58.30 \pm 0.48$ pc). The uncertainty includes contributions from residual errors in the

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[2]`http://www.stsci.edu/$\sim$inr/cmd.html`

geometric-distortion calibration of the FGS, errors in *HST* pointing performance, and errors in the raw stellar position measurements. The resulting proper-motion components for HD 140283 from the FGS solution are $(\mu_\alpha, \mu_\delta) = (-1114.50 \pm 0.12, -304.59 \pm 0.11) \, \mathrm{mas \, yr^{-1}}$, which agree very well with the absolute proper motion determined by *Hipparcos*, $(-1114.93 \pm 0.62, -304.36 \pm 0.74) \, \mathrm{mas \, yr^{-1}}$. The tangential velocity of HD 140283 is thus $319.3 \, \mathrm{km \, s^{-1}}$, and its total space motion relative to the Sun, taking into account the radial velocity of $-169.0 \, \mathrm{km \, s^{-1}}$, is $361.3 \, \mathrm{km \, s^{-1}}$.

4. The Age of HD 140283

Our FGS parallax for HD 140283, together with an apparent visual magnitude $V = 7.205 \pm 0.02$ (Casagrande et al. 2010) and $E(B - V) = 0.000 \pm 0.002$ (Meléndez et al. 2010), yields a visual absolute magnitude $M_V = +3.377 \pm 0.027$. A recent calibration of the infrared-flux method gives an effective temperature $T_{\mathrm{eff}} = 5777 \pm 55$ K (Casagrande et al. 2010). If this T_{eff} is adopted in high-resolution spectroscopic analyses (Gratton, Carretta, & Castelli 1996; Israelian et al. 2004; Rich & Boesgaard 2009), the resulting iron abundance relative to hydrogen is $[\mathrm{Fe/H}] = -2.40 \pm 0.10$, where values in square brackets are logarithms of the abundances by number, normalized to the solar values. According to stellar models that allow for diffusive processes and extra (turbulent) mixing to limit the efficiency of gravitational settling (Richard et al. 2002), the $[\mathrm{Fe/H}]$ measured at the stellar surface will be ∼0.1 dex lower than its value in the interior. We therefore adopt $[\mathrm{Fe/H}] = -2.3$ for our interior stellar models of HD 140283.

To determine the age of HD 140283, we employed evolutionary tracks and isochrones computed using the current version of the University of Victoria code (VandenBerg et al. 2012), with an adopted helium abundance by mass of $Y = 0.250$, slightly above recent estimates of the primordial He abundance, $Y_0 = 0.2486$ (Cyburt, Fields, & Olive 2008).

The Victoria models take into account current values for nuclear-reaction rates (see §§1–2), and include the diffusive settling of helium. Diffusion of elements heavier than He is not treated, apart from the small adjustment to [Fe/H] = −2.3 described above, but the effect of this neglect on derived ages is very small.

At low metallicities, the locations of the turnoff and subgiant portions of isochrones in the HRD depend most strongly on the absolute abundance of oxygen (e.g., VandenBerg et al. 2012), and less so on the abundance of iron and other heavy metals. For example, if [O/H] is fixed at −1.4, nearly the same isochrones are obtained if [Fe/H] = −2.3 and [O/Fe] = +0.9, or if [Fe/H] = −1.9 and [O/Fe] = +0.5. Unlike oxygen, helium is predicted to have almost no impact on the location of the subgiant branch in the HRD, as first shown by Carney (1981; see also VandenBerg et al. 2012, Fig. 18). Thus the age of HD 140283 is essentially independent of Y. This is fortunate because helium lines are not detectable in the spectra of cool stars, and thus the abundance of He cannot be measured directly.

The crucial oxygen abundances in metal-poor G-type stars like HD 140283 can be determined using three different spectroscopic features: the forbidden [O I] line at 6300 Å, the high-excitation permitted O I triplet at 7771–7775 Å, or molecular OH bands in the optical ultraviolet or infrared. As reviewed by many authors (e.g., Asplund 2005; Meléndez et al. 2006; Fabbian et al. 2009b), each of these methods have difficulties: the [O I] line is extremely weak and potentially blended; the permitted O I lines are affected by departures from local thermodynamic equilibrium; and the OH bands are subject to problems of three-dimensional effects in the stellar atmosphere (i.e., granulation), blends, and continuum placement.

Recent determinations of the [O/H] ratio in HD 140283 using all three of these methods (for example, Nissen et al. 2002; Meléndez et al. 2006; Rich & Boesgaard 2009; Tan et al. 2009) have ranged from [O/H] = −1.55 to −1.78 (corrected to the temperature adopted here

of $T_{\rm eff} = 5777$ K using the parameter dependencies given by the cited authors), with errors typically of order ± 0.1–0.15 dex. The unweighted mean of these authors' determinations is about $[{\rm O/H}] = -1.67$, corresponding to $[{\rm O/Fe}] \simeq +0.7$. Corrected for diffusion, the initial oxygen abundance would have been higher by ~ 0.13 dex (Richard et al. 2002, their Fig. 13), resulting in $[{\rm O/H}]_0 = -1.54$. We convert this to the absolute O abundance by using a solar value of $\log N({\rm O}) = 8.69 \pm 0.05$ (Asplund et al. 2009).

The top panel in Figure 1 shows the position of HD 140283 in the semi-theoretical HRD (M_V vs. $\log T_{\rm eff}$) along with isochrones derived for ages of 13.4, 13.9, and 14.4 Gyr. The implied age is 14.46 Gyr. The uncertainty in the age due only to the errors in parallax, photometry, and extinction is only ± 0.31 Gyr, about one-fifth of that associated with previous age determinations based on the *Hipparcos* parallax (VandenBerg et al. 2002). Other contributors to the error budget are summarized in Table 1, and are due to uncertainties in the stellar parameters and composition, dominated by the uncertainty in the $[{\rm O/H}]$ ratio. The total error in the age is about ± 0.8 Gyr (calculated by combining the errors independently in quadrature; this is an approximation because there may be correlations between, e.g., errors in $T_{\rm eff}$ and derived abundances; we did not attempt to model these, since $[{\rm O/H}]$ is the dominant source of uncertainty).

The age of HD 140283 does not conflict with the age of the Universe, given the ± 0.8 Gyr uncertainty. The middle and lower panels in Figure 1 illustrate the sensitivity of the age to an increased oxygen abundance. If $[{\rm O/H}]$ is increased by 0.15 dex, which is roughly the uncertainty in the measured abundance, the age of HD 140283 is reduced to about 13.8 Gyr. Increasing $[{\rm O/H}]$ by 0.30 dex reduces the age to ~ 13.3 Gyr.

In summary, the age determination for HD 140283 depends primarily on its oxygen abundance relative to hydrogen, with its parallax now having been removed as an important contributor to the error budget. The most important reasons for differences between our

new result and that of VandenBerg et al. (2002) are the inclusion of diffusion, new nuclear reaction rates, adoption of $E(B - V) = 0.00$ instead of 0.025, and the much more precise parallax.

5.   Implications

HD 140283 is the oldest known star for which a reliable age has been determined—but of course it is not quite a primordial star, given its low but non-zero metallicity. Our precise distance could enable HD 140283 to be used as a "standard candle" to determine the distances to very metal-deficient GCs and nearby metal-poor dwarf galaxies (which appear to be coeval with GCs—Brown et al. 2012), by fitting their subgiant branches to the luminosity of HD 140283. However, this would result in a distance to the GC M92 smaller by ∼0.1–0.2 mag than nearly all other distance estimates. This discrepancy would be reduced (and the implied age of HD 140283 also reduced) if the star is slightly reddened. Setting $E(B - V) = 0.02$, in spite of the zero value found by Meléndez et al. (2010), would reduce its age by ∼0.65 Gyr.

There is a remarkable accordance (within their respective uncertainties) between the age of the Universe inferred from the CMB, the age of the chemical elements (Roederer et al. 2009), and the ages of the oldest stars. The difficulty of determining accurate abundances, especially [O/H], will continue to limit the accuracy of stellar age determinations for the foreseeable future, including the era when accurate distances out to a few kpc are obtained from *Gaia* (Perryman et al. 2001).

Facilities: Hubble Space Telescope, SMARTS 1.3- and 1.5-m telescopes, WIYN 3.5-m telescope

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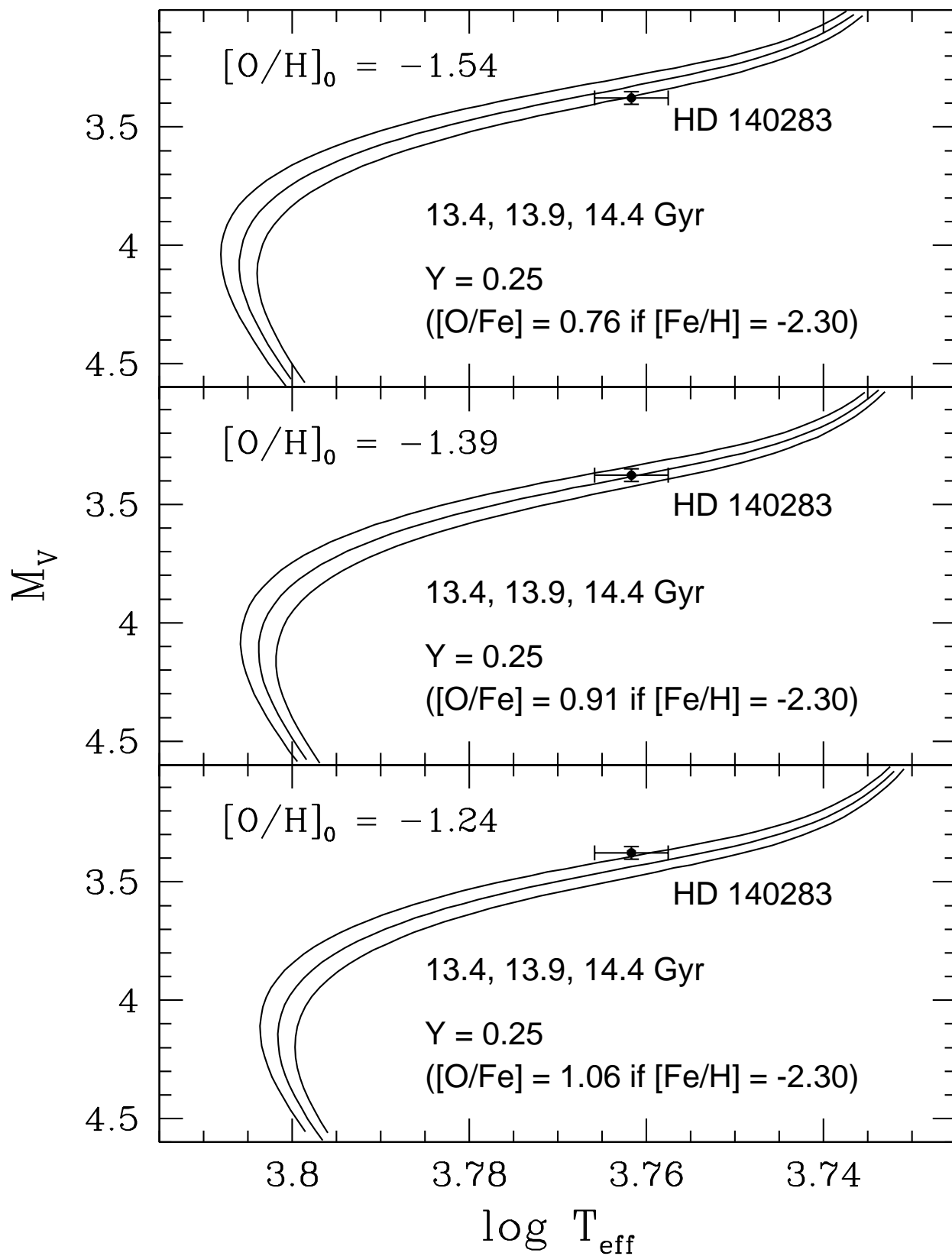Zacharias, N., Finch, C., Girard, T., et al. 2012, arXiv:1212.6182

Fig. 1.— *Top panel:* Theoretical University of Victoria isochrones, plotted in the $(\log T_{\mathrm{eff}}, M_V)$ plane, for stellar ages of 13.4, 13.9, and 14.4 Gyr. The plot is magnified to show only the subgiant portion, lying between the main-sequence turnoff to the lower left and the base of the giant branch to the upper right. For the composition in the stellar interior, we used a helium abundance of $Y = 0.25$, an iron abundance of $[\mathrm{Fe/H}] = -2.3$, and an initial oxygen abundance of $[\mathrm{O/H}] = -1.54$. The point with error bars shows the location of HD 140283. The implied age is 14.46 ± 0.31 Gyr, where the error bar is the uncertainty due only to the error in the *Hubble Space Telescope* trigonometric parallax. The systematic error in the age due to uncertainties in the effective temperature and chemical composition is larger, about ± 0.8 Gyr (see text). *Middle and lower panels:* Theoretical isochrones for ages of 13.4, 13.9, and 14.4 Gyr, with the initial $[\mathrm{O/H}]$ abundance ratio increased by 0.15 and 0.30 dex, decreasing the implied age of HD 140283 to about 13.8 and 13.3 Gyr, respectively. The uncertainty in the initial oxygen abundance is now the largest contributor to the uncertainty in the age.

Table 1.   Error Budget for Age of HD 140283

Quantity	Value	Uncertainty	$\sigma(\text{age})$ [Gyr]
Parallax	17.15	± 0.14 mas	0.21
V	7.205	± 0.02 mag	0.23
$E(B-V)$	0.000	± 0.002 mag	0.06
T_{eff}	5777	± 55 K	0.35
[Fe/H]	-2.40	± 0.10 dex	0.10
[O/H]	-1.67	± 0.15 dex	0.61
Solar $\log N(\text{O})$	8.69	± 0.05 dex	0.20
Total uncertainty			0.80

Note. — Sources of values and error estimates are given in text.